

INTEGRAL - OPERATING HIGH-ENERGY DETECTORS FOR FIVE YEARS IN SPACE

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The *INTEGRAL* satellite, which studies the Universe in the hard X-ray and soft Gamma-ray domain, has been operational for 5 years now. The X-ray telescopes, which use the coded mask technique, provide unprecedented spectral and imaging resolution. This led to a number of discoveries, such as the distribution of diffuse emission in the Galaxy, the discovery of highly absorbed sources and fast X-ray transients in the Galactic Plane, localization of ~ 50 Gamma-ray bursts, and the resolution of the cosmic X-ray background around its peak at 30 keV. About 300 previously known X-ray sources have been detected and in addition more than 200 new sources have been discovered. *INTEGRAL* provides spectra starting at 3 keV and ranging up to several hundred keV. This article gives a brief overview about the major discoveries of *INTEGRAL*.

Keywords: Astrophysics; Gamma-rays; X-rays.

1. The INTEGRAL Mission

ESA's *INTEGRAL* space mission [1] hosts two major hard X-ray instruments, IBIS and SPI, both coded-mask telescopes. IBIS [2] provides imaging resolution of 12 arcmin, while SPI [3] is optimized for spectroscopy. Both instruments operate at energies from 15 keV up to several MeV. Co-aligned with these main instruments are the two X-ray monitors JEM-X [4], which provides spectra and images in the 3–30 keV band, and the optical camera OMC [5], which provides photometry in the V filter. *INTEGRAL* was launched on October 17, 2002 from Baikonur into a highly eccentric orbit with a perigee of 9,000 km and an apogee of 150,000 km, which avoids as much as possible the Earth's radiation belt and allows for un-interrupted observations of up to 3 days.

2. Data processing for INTEGRAL and the ISDC

Data from the *INTEGRAL* mission is made available to the community via the *INTEGRAL Science Data Centre* (ISDC [6]). The telemetry of the satellite is sent in a constant data flow of $\sim 90 \text{ kbits s}^{-1}$ to the Mission Operations Centre in Darmstadt. From there the data are then sent to the ISDC in Versoix (near Geneva). Incoming data are searched for transient sources and Gamma-Ray bursts within a few seconds after arrival by the *INTEGRAL Burst Alert System* (IBAS [7]). The telemetry data are pre-processed, which means that they are decoded and data are stored into a fits file data structure. Afterwards the data are analysed by a scientist on duty in order to look for scientifically interesting events, such as the occurrence of new sources, and to inform the astrophysical community. The data are then archived together with standard analysis results and distributed to the scientific community. In addition, the ISDC provides scientific analysis software to the community, in collaboration with the instrument teams. The software, documentation and *INTEGRAL*'s data are available through the ISDC web-page^a.

3. Scientific Highlights

Within the first five years of the mission *INTEGRAL* related research led to several hundreds of scientific publications. Below I will present a few of them, focussing on most recent discoveries. This list is obviously incomplete and biased, and I refer the reader to the list of *INTEGRAL* related publications maintained at ESA/ISOC^b.

3.1. The Galactic Centre

Using ISGRI [8], the soft γ -ray detector of IBIS, it was for the first time possible to resolved the Galactic Centre above 20 keV. A new source, IGR J1745.6–2901, was found to be the hard X-ray counter part of Sgr A*, which appears to be a faint but persistent source at this energy with a spectrum which apparently originates from a two temperature plasma with $kT \simeq 1.0 \text{ keV}$ and $kT \simeq 6.6 \text{ keV}$ [9]. The source seen by *INTEGRAL* is also detected at TeV energies by HESS [10]. ISGRI also detected another new source close by, which has been associated with the giant molecular cloud Sgr B2 [11]. This cloud might reflect the emission of Sgr A* in the X-rays

^aThe ISDC web page is located at <http://isdc.unige.ch/>

^b<http://www.sciops.esa.int/index.php?project=INTEGRAL>

and therefore function as a “Compton mirror” [12]. If this hypothesis is true, the emission of the central black hole of our Galaxy was much higher about 300 – 400 years ago than it appears today.

3.2. Compact Objects

Galactic compact objects are the brightest persistent sources seen by *INTEGRAL*. Therefore during the first five years of the mission, the majority of observing time was used to cover the Galactic Centre and the Galactic Plane, revealing not only a large number of new sources, but also allowing for the first time to monitor in detail the spectral evolution of known hard X-ray sources. Within the class of black hole candidates especially Cygnus X-1 led to many new results, such as the detection of a hard tail in the spectrum in excess of the thermal Comptonization [13], and the complex nature of the physical processes involved in state transitions [14,15]. In the case of GRO J1655–40, the interpretation of a bright burst observed in 2005 is still ongoing, as some studies find evidence for a spectral cut-off at high energies [16], whereas others find an undisturbed power law up to several hundreds of keV [17,18]. In addition the number of black hole candidates with well studied spectra increased significantly with *INTEGRAL*. This includes the cases of XTE J1550–564 where an underluminous outburst was observed [19], XTE J1817–330, in which the ISGRI data indicate a thermal accretion disk and a comptonizing hot corona [20], 4U 1630–47 shows a variety of high-amplitude variability occurring at the highest disk luminosities [21], and also newly discovered black hole candidates like IGR J17464–3213 [22].

Extending the spectra into the soft γ -ray range, *INTEGRAL* shows that many low mass X-ray binaries (LMXB) indeed have variable “hard tails” [23], which most likely originate in the Compton cloud located inside the neutron star’s magnetosphere [24]. Concerning the pulsars, the enigmatic rotating neutron stars, cyclotron lines can now be measured in greater detail, e.g. in A 0535+26 [25], or in the anomalous X-ray Pulsar 4U 0142+614, which shows a complex spectrum and timing behaviour in the hard X-rays [26]. The anomalous X-ray pulsars show very hard and pulsed X-ray emission, which indicates that these sources are indeed magnetars [27]. The observation of the outburst of the pulsar V0332+53 [28] has led to the discovery that the brightness decline is accompanied by a change in the extent of the cyclotron scattering region [29], gave detailed insight into its orbital parameters [30] and geometry [31], and revealed that the energies at which the cyclotron lines appear change linearly with

the source luminosity [32]. Several pulsars have been shown to be accretion powered, such as the newly discovered pulsars IGR J00370+6122 [33] and IGR J18483-0311 [34], and 4U 1954+319 turned out to be a symbiotic LMXB with the slowest wind-accreting X-ray pulsar ever observed [35]. On the other hand, *INTEGRAL* also discovered the fastest millisecond pulsar ever known, the new source IGR J00291+5934 [36]. The accreting Be/X-ray pulsar SAX J2103.5+4545 has been a puzzling object, as it was seen exhibiting hard/high and soft/low states [37] and large spin-up rate [38,39].

Microquasars have been also studied in great detail. GX 339-4 displays a variable high energy cut-off which might suggest that the low- and high-energy components in this source have a different origin [40]. The X-ray binary LSI +61 303 also seems to host a microquasar, but does not reveal the presence of a cut-off, and the observed spectrum and spectral variability can be explained if the compact object in the system is a rotation powered pulsar [41]. LS 5039, the only persistently detected X-ray binary at TeV energies, has been detected by IBIS/ISGRI and the data hint to a break in the spectral behaviour at hard X-rays [42]. For GRS 1915+105 new variability patterns have been discovered [43], whereas the case of Cyg X-3 and whether or not it hosts a microquasar remains a question of debate [44,45].

3.3. New Sources found by *INTEGRAL*

Since the launch of the mission, *INTEGRAL* has discovered more than 200 previously unknown hard X-ray sources^c. As most of the new sources were discovered along the Galactic Plane, optical identification of the counterpart is often difficult. Several projects aim at this problem, for example by comparing the *INTEGRAL* sources with photometric catalogues [46] or with the ROSAT catalogues [47], by optical spectroscopy (e.g. [48,49]), or by simultaneous multi-telescope follow-up observations (e.g. [50]). Despite these efforts, more than 50% of the new discoveries remain unclassified. Among the Galactic sources, *INTEGRAL* discovered a number of highly absorbed high mass X-ray binaries (HMXB), in which the binary system is obscured by the strong stellar wind originating from the massive donor star [50–52]. Another study suggests that the obscured sources may be microquasars like SS 433, but with slightly lower mass transfer rate [53]. Another class of rare objects found are HMXB with lower absorption, the

^cSee the webpage listing the new sources discovered by *INTEGRAL* under <http://isdc.unige.ch/~rodrigue/html/igrsources.html>

Supergiant Fast X-ray Transients (SFXT). In these sources the X-ray emission might appear when the neutron star crosses the stellar wind of the giant star [54], or could be due to several wind components [55]. The majority of the new sources seems to be distributed in the Galactic Plane rather like the LMXB than the HMXB population [56]. The extended mission of *INTEGRAL* allows now also to detect fainter sources, like the magnetic CV IGR J00234+6141 of the intermediate polar type. The discovery of this type of object confirms earlier conclusions that intermediate polars contribute significantly to the population of galactic X-ray sources and represent a significant fraction of the high energy background [57]. Lately it has also been shown that several unidentified sources detected in the TeV range are counterparts of *INTEGRAL* sources [58,59]. While for point-like and variable TeV sources the correspondence with the *INTEGRAL* sources is almost sure, we seem to observe different acceleration sites in the case of extended sources like supernova remnants and pulsar wind nebula [60].

In the extragalactic sky *INTEGRAL* detected more than 160 AGN, mainly Seyfert galaxies, of which many were not known to be hard X-ray emitters [56,61].

3.4. Active Galactic Nuclei and the CXB

With the wide spectral coverage, *INTEGRAL* was used to study in detail several bright AGN. The AGN detected by IBIS/ISGRI above 20 keV are on average low luminous and near-by ($\bar{z} = 0.02$) Seyfert galaxies [62–64]. In the hard X-rays the absorption by Galactic hydrogen does not affect the spectra, thus *INTEGRAL* can observe AGN shining through the Galactic Plane [65,66]. In most of the AGN it appears that the spectral turn-over from a simple power law is located at energies $\gg 100$ keV, as shown in the Seyfert 2 galaxy NGC 4388 in which the absorbing material is probably far from the central engine [67], NGC 4151 [68], NGC 2992, the most variable Seyfert of the bright AGN seen by *INTEGRAL* [69], Cen A [70], and in a spectral study of 72 AGN combining data from all three X-ray instruments on board the satellite [62]. The objects with sufficient signal-to-noise show though signatures of Compton reflection [68,71], but only a dozen AGN have been detected by IBIS/ISGRI above 100 keV so far [72]. Only about 10 blazars have been detected and studied so far, such as S 0716+714 [73], 3C 454.3 [74], which both were observed after an outburst. The lowest redshift quasar 3C 273 shows a historic minimum in its X-ray emission [75, 76], which allows to study the spectral features usually hidden by the strong jet emission [77], and lately the farthest object seen so far by *INTEGRAL*

has been detected: IGR J22517+2218 which is spatially coincident with MG3 J225155+2217, a quasar at $z = 3.668$ [78].

Related to the compilation of AGN surveys in the hard X-rays is the question of what sources form the cosmic X-ray background (CXB) which peaks at an energy of about 30 keV. An early study seemed to indicate that a large fraction of low luminous AGN contributes to the CXB [79], but apparently these source detections were spurious and could not be confirmed by later studies. Number counts of AGN and the construction of the X-ray luminosity function remains one of the major aspects of current *INTEGRAL* related AGN research. The first luminosity function derived in this energy range indicated that the *INTEGRAL* detected AGN cannot explain the CXB without evolution of the AGN population [80], and a recent study indicates that the CXB can be explained when considering luminosity dependent density evolution [64]. On the contrary, a study on the *XMM-LSS* field came to the conclusion that an evolution in absorption (towards stronger absorbed sources at higher redshifts) has to be assumed in order to connect the CXB to *INTEGRAL* detected AGN [81]. In all these studies it has to be taken into account that the exact strength of the CXB is still under debate. *INTEGRAL* measurements of the CXB through Earth-occultation technique seem to indicate that the actual flux is higher by $\sim 20\%$ when compared to earlier HEAO-1 measurements [82].

3.5. *Gamma-Ray Bursts, SGRs, and the IBAS system*

The *INTEGRAL* Burst Alert System (IBAS [7]) monitors the incoming data for events in the Anti-Coincidence System (ACS [83]) of the spectrometer SPI and in the field of view of IBIS. For the latter events which have the signature of a Gamma-Ray Burst (GRB), the coordinates are determined automatically with high precision (usually ~ 2 arcmin uncertainty) and distributed within ~ 20 seconds to the astronomical community. As of October 2007, *INTEGRAL* has detected 47 GRB in the field of view^d. Among those GRB, only one event is a so-called short burst [84,85]. Because of the high sensitivity of IBIS/ISGRI, even faint GRBs are detected and thus *INTEGRAL* was able to see the sub-energetic GRB 031203, the closest to Earth determined so far [86,87]. For the brightest one, GRB 041219a, it was possible to constrain the degree of linear polarisation $63^{+31}_{-30}\%$ [88]. Thanks to IBAS, *INTEGRAL* was the first satellite in 2004 to report the giant flare from the soft gamma-ray repeater SGR 1806-20 [89]. The bright

^dsee <http://ibas.iasf-milano.inaf.it>

flare of this magnetar, i.e. a strongly magnetized neutron star, can be explained by magnetic reconnection caused by crust breaking of the neutron star's surface [90]. Up to now *INTEGRAL* has seen 4 confirmed SGRs and 3 promising candidates [91,92].

The GRB detected by the SPI-ACS are also made public immediately through the web^e. Although no localization is available for these bursts, the ACS provides 50 ms lightcurves for on average one burst every 3 days [93].

3.6. Diffuse Galactic Emission

The Ge detectors of the SPI spectrometer [3] provides a resolution of about 2.5 keV at 1.3 MeV. This is sufficient to resolve Gamma-Ray lines of the Galactic diffuse emission. A prominent line is the 511 keV annihilation line of cosmic positrons. SPI measurements demonstrate that the positrons mainly annihilate with free electrons and that the medium must be at least partially ionized [94]. Another finding is that most of the emission seems to arise from the Galactic bulge and not from the Galactic disk [95], which led to speculations that the source of the diffuse emission is the Galactic black hole Sgr A* [96] or that it might origin from electroweak scale WIMPs [97], from WIMP candidates with an “excited state” [98], or from pulsar winds [99]. Another bright Gamma-ray line at 1808.65 keV arises from the decay of radioactive ²⁶Al. Analysis of SPI data led to the finding that ²⁶Al source regions corotate with the Galaxy, supporting its Galaxy-wide origin and revealing a core collapse supernova rate of 1.9 ± 1.1 per century in our Galaxy [100]. Other gamma-ray lines which have been observed from nucleosynthesis sites include ⁴⁴Ti [101] and ⁶⁰Fe [102]. Gamma-ray lines from point sources, as they were reported from previous Gamma-ray missions with less sensitivity, have so far not been detected and also no “unexpected” lines have been found [103].

Another mystery solved by *INTEGRAL* is the origin of the Galactic background emission at 20–60 keV, which has been demonstrated to arise from compact sources [104], whereas the Galactic ridge emission at soft γ -rays (200 keV – 1 MeV) has been shown to be indeed a diffuse or unresolved emission component which might be caused by in-situ electron acceleration or by an unresolved population of weak sources with hard X-ray spectra [105].

^eFor all alerts from the IBAS system see <http://isdc.unige.ch/index.cgi?Soft+ibas>

4. Outlook

All instruments of the *INTEGRAL* mission are in good health. The recent results have shown that many science projects are only possible through the very deep exposures, available after several years of observation. Not only will the study of the diffuse emission benefit from an on-going *INTEGRAL* project, as it will reveal the true distribution of the positrons, ^{26}Al , ^{60}Fe and other elements resulting from nucleosynthesis in the Galaxy. Especially for source population studies, like for X-ray binaries like LMXB, HMXB, and CVs, and of course for AGN, the continuous observation of the sky with high spectral and spatial resolution above 20 keV will be crucial. Concerning the AGN the question what causes the CXB will be answered, and the true physics in the central engine of Seyfert galaxies and what role Compton reflection plays in there, will be revealed. For Galactic sources the observations of the X-ray binary population will help us to understand the formation of accretion disks around black holes, and their contribution to the Galactic Ridge emission. This will help to disentangle the source mix apparent in our Galaxy. Finally, obscured sources, both Galactic and extragalactic will be discovered, helping us to peer through the obscuring material into the true nature of the most violent physical processes.

Acknowledgments

INTEGRAL is an ESA project funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Spain, Switzerland), Czech Republic, Poland, and with the participation of Russia and the USA.

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